10/070750

6/PRTS

POWER TRANSFORMERS AND POWER INDUCTORS FOR LOW FREQUENCY APPLICATIONS USING ISOTROPIC COMPOSITE MAGNETIC MATERIALS WITH HIGH POWER TO WEIGHT RATIO

FIELD OF THE INVENTION

The present description presents several structures of transformers and inductors one of which is shown in Fig's 1a and 1b using a core 10 which has a cylindrical symmetry (see Fig. 1c) around one main revolution axis 11, with windings 12 only one winding in the inductor case, enclosed in the magnetic core 10. The primary winding 12 of these transformers and/or autotransformers is directly connected to an AC power supply 13 (see Fig. 12) with an operation frequency in the range of 50 Hz to 1000 Hz. The power range of these applications lies between 1 VA and 10kVA. The materials used for the realization of the magnetic cores 10 of these devices are isotropic soft magnetic composite materials, made of iron powder and resin.

The proposed structures are maximizing the power to weight ration of the devices. These devices can be used alone or in association with rectifiers 14 which use diodes and/or thyristors and/or transistors to provide the power supply which is used in equipment having electronic components circuits. The devices can also be used to construct distribution transformers, isolation transformers and inductors with or without low profile.

BACKGROUND OF THE INVENTION

Since the end of the 19th century, laminated soft magnetic materials have been used for the construction of single or polyphase transformers and inductors for applications in the usual commercial range of AC supply

frequency (from 50 Hz to 1000 Hz) for a wide power range (from 1VA to several kVA). These isolated laminations present interesting magnetic properties with a high level of induction of saturation (near 1.8 T). The isolation of the laminations also allows the minimization of the magnetic losses because the magnetic flux is circulating in the plane of the laminations (the flux is circulating in two dimensions only). The shapes of the magnetic core are then imposed by this constraint and limited to a toroïd shape, and E, C or I-shape (E-core, C-core or I-core) and all combinations of these topologies.

The cost of the assembly of these devices is relatively high, because the production process needs an important number of steps including lamination forming, punching, mounting and stacking, insertion of the winding and isolation, mounting of the external support and the terminal plate. These transformers are commercially available in standard sizes to cover a wide power range.

One drawback of the lamination use is the generation of an important audible noise for the usual values of frequency of the AC supply systems in the range from 50Hz to 1000Hz (50, 60 or 400 Hz for example) see U.S. Patent No. 529051 to Inokuti; Yukio et al. "Method of producing low iron loss grain oriented steel having low noise and superior shape characteristics". The electrical insulation between laminations also reduces in great proportions, the heat transfer between the laminations, and the main part of the heat is circulating in the plane of the laminations, i.e. in two dimensions only. The contribution of the magnetic core for the transfer of the heat generated by the copper losses in the windings and the magnetic losses in the core to the

ambiance is therefore limited. In such structures using laminations, the temperature rise between the windings and the laminations remains an important limitation in terms of power to weight ratio.

The variations of the permeability of the magnetic materials used in laminations are very important when saturation is occurring. It is then necessary to oversize the transformers and inductors to avoid saturation in the case of voltage variations of the AC supply. When saturation occurs, the magnetizing current can increase in great proportions and produce an excessive heating of the windings.

The conventional shapes of magnetic cores like E, C and I-configuration cores do not maximize the power to volume and power to weight ratios of the transformers and inductors. In these structures, there are also important magnetic stray fields and leakage flux which circulate in the external environment of the device and can induce parasitic perturbations in electrical or electronic circuits, for example. In applications where the stray magnetic radiation of the transformer or the inductor must be eliminated, magnetic cores with a toroïdal shape are generally used (transformers used in power supplies of audio amplifiers for example) see U.S. Patent No.3,668,589 by Wilkinson "Low frequency magnetic core inductor structure". But the winding process on such a core is difficult and the transfer of the heat generated by copper losses in the windings and magnetic losses in the core to the ambiance, in such transformers and inductors, is not efficient.

The magnetic cores which present a cylindrical symmetry around one main revolution axis with windings enclosed are the best suitable for the realization of

transformers and inductors. In such structures, there is an optimal use of the copper volume and a good magnetic coupling between the windings. The power to weight ratio and the power to volume ratio are maximized. But it is impossible to realize this shape of magnetic core with laminations, because in the cores which present a cylindrical symmetry around one main revolution axis with windings enclosed, the magnetic flux is circulating in the three dimensions. It is necessary to use an isotropic soft magnetic material with a low electrical conductivity.

Since 30 years, magnetic cores which present a cylindrical symmetry (Pot-cores for example) have been realized with isotropic sintered soft magnetic materials with low electrical conductivity like ferrites for high frequency power supplies (20 kHz to 300 kHz) see U.S. Patent No. 4,602,957 to Pollock et al, "Magnetic powder compacts". The magnetic and thermal properties of these materials are isotropic and their magnetic losses are minimized on a wide range of frequency up to 500 kHz and several Mhz see US Patent 4,507,640 to Rich III et al, "High frequency transformer". Several distributors, such as Philips, Siemens, etc, are already offering a wide range of standard size ferrite cores with different shapes C, E and I-cores, toroïd cores, ETD-cores and Pot-cores, to realize high frequency transformers and inductors. But, at low frequency, the power to weight ratio of the transformers and inductors is also proportional to the value of the induction of saturation of the soft magnetic material. The induction of saturation of the ferrite material which is relatively low, near 0.4 T, is limiting the use of such a material for applications at low values of frequency used in the conventional AC supplies

systems, from 50Hz to 1000Hz, for example 50Hz, 60Hz and 400Hz. The use of ferrite materials is then limited to high frequency applications. Because they are sintered, the ferrite materials are also brittle and the size and shape of the cores which can be realized are therefore limited. For example, because these materials are brittle, it is not possible to press cooling fins directly on the cores during forming.

Other kinds of magnetic materials have been proposed for the realization of Pot-Core transformers for low or high frequency applications as disclosed in U.S. Patents 4,601,765 to Soileau et al and 4,201,837 to Lupinski. Generally the sintered materials present a high cost of production and the cores which are proposed don't have cooling fins on their external surface to maximize the power to weight ratio.

Several new soft magnetic composites have been recently developed in the domain of powder metallurgy. (ATOMET EM-1 of Quebec Metal Powders Inc for example, see I C.Gélinas, L.P. Lefebvre, s. Pelletier, P. Viarouge, Effect of Temperature on Properties of Iron-Resin Composites for Automative Applications, SAE Technical Paper (7p.) 970421 Eng. Soc. for Advancing Mobility Land Sea Air and Space. Int. Congress Detroit Michigan February 24-27 1997. In such soft magnetic isotropic materials, the iron flakes are isolated from each other by a resin coating. These materials need a pressing process and a thermal treatment at low temperature. Their cost of production is then reduced. These materials are more adapted to applications where a mass production is necessary, despite the fact that their production cost per

kilogram remains higher than the one of laminations (near two times higher).

By using a molding technique, it is possible to realize a core of complex shape in a single operation. It is also possible to machine the soft magnetic composites with conventional tools, while the sintered materials like soft magnetic ferrite can be only rectified with diamond grinding wheels.

The use of the soft magnetic composites for applications in the low frequency domain from 50Hz to 1000Hz is not still developed because these materials present a relatively low value of permeability when compared to the value of the permeability of laminations. (the relative permeability of the soft magnetic composites is near 200 and 1500 for the conventional grades of laminations).

The magnetic losses at 50Hz and 60Hz in the soft magnetic composites are higher than in the soft magnetic laminated materials. (near 5 to 15 W/kg at 1.2 T instead of 2 W/kg for the soft magnetic laminated materials). But at 400Hz, the magnetic losses of some soft magnetic composites can be 2 times lower see the above-referred technical paper.

DISCLOSURE OF INVENTION

We have found that despite the fact that soft magnetic composite materials do not present, at first sight, interesting magnetic characteristics for the realization of transformers (relative permeability near 120 at 1.2 T), the use of magnetic cores made of isotropic soft magnetic composite material with a structure presenting a cylindrical symmetry around one main revolution axis with windings enclosed, can be used to increase the power to weight and

power to volume ratios when compared to the transformers using a conventional core structure made of laminations.

If the core structure presenting a cylindrical symmetry around one main revolution axis with windings enclosed is equipped with integrated cooling fins made of the soft magnetic composite material itself, it is possible to increase the power to weight ratio, because the external surface of dissipation of the core and the transfer of the heat generated by the copper and magnetic losses to the ambiance are increased. In the present invention, we propose to directly form these cooling fins with the soft magnetic composite material itself because the mechanical properties of such materials allow this kind of realization during the pressing process. These cooling fins do not need any other fabrication step because they are pressed directly with the core itself. But it is also possible to realize them by machine finishing (machining) of the core after the pressing process. These kinds of cooling fins are also more efficient in terms of heat transfer when compared to conventional aluminum fins which can be attached to the magnetic core, because there no contact thermal resistance between the magnetic structure and the fins.

It is pointed out that the thermal conductivity of the soft magnetic composite materials is similar to the thermal conductivity of iron. But the thermal properties of the soft magnetic composite materials are also isotropic, and the thermal conductivity presents the same value in the three dimensions. Consequently, the temperature rise of the winding above the ambiance remains low, and it is thus possible to achieve designs with a further reduction of the total mass of the device. The magnetic flux can also circulate in the

kilogram remains higher than the one of laminations (near two times higher).

By using a molding technique, it is possible to realize a core of complex shape in a single operation. It is also possible to machine the soft magnetic composites with conventional tools, while the sintered materials like soft magnetic ferrite can be only rectified with diamond grinding wheels.

The use of the soft magnetic composites for applications in the low frequency domain from 50Hz to 1000Hz is not still developed because these materials present a relatively low value of permeability when compared to the value of the permeability of laminations. (the relative permeability of the soft magnetic composites is near 200 and 1500 for the conventional grades of laminations).

The magnetic losses at 50Hz and 60Hz in the soft magnetic composites are higher than in the soft magnetic laminated materials. (near 5 to 15 W/kg at 1.2 T instead of 2 W/kg for the soft magnetic laminated materials). But at 400Hz, the magnetic losses of some soft magnetic composites can be 2 times lower see the above-referred technical paper.

DISCLOSURE OF INVENTION

We have found that despite the fact that soft magnetic composite materials do not present, at first sight, interesting magnetic characteristics for the realization of transformers (relative permeability near 120 at 1.2 T), the use of magnetic cores made of isotropic soft magnetic composite material with a structure presenting a cylindrical symmetry around one main revolution axis with windings enclosed, can be used to increase the power to weight and

winding is enclosed in the magnetic core and disposed about a central column of the magnetic core and magnetically coupled with the magnetic core. The core is formed by core sections.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the present invention will now be described with reference to the accompanying drawings in which

Fig.1a is a top view of a section of a magnetic core constructed in accordance with the present invention and having a cylindrical symmetry around one main revolution axis and a circular cross-section of the winding window and the magnetic core;

Fig. 1b is a side view of Figure 1a;

Fig. 1c is a side view of an assembly of two core sections of Figures 1a and 1b;

Fig. 2a is a side view of the magnetic circuit for an inductor application showing an air gap between the two sections of the core;

Fig. 2b is another side view showing an air gap at the center of the core;

Fig. 3a is a top view along section lines A-A' of Figure 3b, presenting a core with a cylindrical symmetry around one main revolution axis and a circular cross-section of the winding window and the magnetic core;

Fig. 3b is a section view along section line B-B of Figure 3a;

Fig. 4a is a top section view of the magnetic core as seen along section lines A-A of Figure 4b, presenting a cylindrical symmetry around one main revolution axis and a

rectangular cross-section, with round corners, of the winding window and end of magnetic core;

Fig. 4b is a section view along section lines B-B of Figure 4a;

Fig. 5a is a top view along section lines A-A of Figure 5b showing the magnetic core presenting a cylindrical symmetry around one main revolution axis and a rectangular cross-section of the winding window and the magnetic core;

Fig. 5b is a section view along section lines B-B of Figure 5a;

Fig. 6a is a top section view along section lines A-A of Figure 6b illustrating the magnetic core presenting a cylindrical symmetry around one main revolution axis, a rectangular outer cross section of the core and a trapezoidal cross section of the winding window;

Fig. 6b is a section view along section lines B-B of Figure 6a;

Fig. 7a is a top section along section lines A-A Figure 7b illustrating the magnetic core presenting a cylindrical symmetry around one main revolution axis, a trapezoidal outer cross-section of the core and a rectangular cross-section of the winding window;

Fig. 7b is a section view along section lines B-B of Figure 7a;

Figures 8a and 8b are side and top views of a magnetic core constructed in accordance with the design of Figure 1c but with the core provided with fins;

Figures 9a and 9b are side and top views respectively showing a core constructed in accordance with the embodiment of Figure 4b but with fins provided about the core;

Figures 10a and 10b are side and top views respectively of a core constructed in accordance with the embodiment of Figure 5b but with fins extending about the side wall of the core;

Fig. 11a is a top section view along section lines AA of the core as shown in Figure 11b illustrating a slot formed in each of the core sections;

Fig. 11b is a side view of Figure 11a;

Fig. 11c is a further top section view along section lines AA of Fig. 11b showing a plurality of slots formed in the core for reducing the circulation of Eddy currents therein;

Fig. 11d is a side view of the core of Figure 11c; and

Fig. 12 is block diagram showing an application of the transformer with one or several secondary windings and connected to a rectifier circuit and for use as a DC supply for electronic components.

DESCRIPTION OF PREFERRED EMBODIMENTS

The present description presents several structures of transformers and inductors one of which is shown in Fig's 1a and 1b using a core 10 which has a cylindrical symmetry (see Fig. 1c) around one main revolution axis 11, with windings 12 only one winding in the inductor case, enclosed in the magnetic core 10. The primary winding 12 of these transformers and/or autotransformers is directly connected to an AC power supply 13 (see Fig. 12) with an operation frequency in the range of 50 Hz to 1000 Hz. The power range of these applications lies between 1 VA and 10kVA. The materials used for the realization of the magnetic cores 10 of these devices are isotropic soft magnetic composite materials, made of iron powder and resin.

The proposed structures are maximizing the power to weight ration of the devices. These devices can be used alone or in association with rectifiers 14 which use diodes and/or thyristors and/or transistors to provide the power supply which is used in equipment having electronic components circuits. The devices can also be used to construct distribution transformers, isolation transformers and inductors with or without low profile.

The cores 10 are realized by a machining or pressing process of an isotropic soft magnetic composite material composed of iron and resin.

With the solutions which are presented, it is possible to produce transformers 15 and inductors 16 (see Fig. 12) with a power to weight ratio which is higher than in the case of the classical structures of transformers and inductors which use laminations.

Referring to Fig. 1a to 4b it can be seen that the shapes of the structures which are proposed in this invention present a cylindrical symmetry around one main revolution axis 11, and the winding or the windings 12, 12' are enclosed in the magnetic core 10. In the plane of the cylindrical symmetry (a plane passing through the revolution axis), the cross-section of the winding window 16 and the magnetic core 10 can be rectangular (Fig. 5b), circular (Fig. 3b) or oval (Fig. 4b). With such an arrangement, it is possible to get a good coupling between the windings 12, and to minimize the external stray magnetic fields, because the shielding effect of the magnetic core 10. The audible noise is also eliminated because a soft magnetic composite material is used.

The magnetic core 10 is realized in two identical parts or sections 10' and 10", to simplify the production process and the windings 12 and 12' are placed around the central column 17 of the magnetic core. One or two holes 18 with a small diameter can be realized in the base or on one side of the two sections of the core 10 to connect the output wires of the internal winding or windings to the external output terminals (not shown) of the transformer or inductor.

The magnetic core 10 of an inductor can present an airgap 19 realized by separating its two sections 10' and 10" (Fig 2a) or by using a central column and an external shell of different lengths (Fig 2b). In this case, it is preferable to make an airgap 19' on the central column 17 to minimize the external magnetic stray fields. It is also possible to increase the central airgap to eliminate the central column.

The shapes of the cross-section of the winding window 16 and the core in the plane of the cylindrical

symmetry, a plane passing through the revolution axis 11, can be different.

With a circular cross-section as shown in Fig's 1a to 1c, it is possible to minimize the total amount of magnetic material and to reduce the iron losses , because the repartition of the flux lines is homogeneous and there is no local saturation like in the corners of the window of the structure with a rectangular cross-section as shown in Fig's 5a and 5b.

It is also possible to use an oval cross-section or a rectangular cross-section with round corners Fig. 4b). This structure of core is more adapted to the pressing process of the soft magnetic composites than the structure of Fig's 5a and 5b, and it presents the same advantages.

It is also possible to use a trapezoidal cross-section of the winding window with a rectangular external cross-section 20 of the core as shown if Fig. 6b, or a rectangular cross-section of the winding window 16 with a trapezoidal external cross-section 21 of the core as shown in Fig. 7b. These structures of core are minimizing the total amount of magnetic material but not so perfectly than the structure of Fig's 1a to 1c.

All the proposed cores 10 of Fig's 1a to 7b can be realized with different values of form factor (ratio between the height and the external diameter of the core) to be adapted to specific constraints of the applications. Low profile transformers or inductors can be easily realized with a low cost of production because the use of soft magnetic iron-resin composites. For example low profile inductors and transformers are well adapted to the implementation on

electronic cards in racks with a limited interval between cards as discussed in U.S. Patent 5,175,525..

With reference to Fig's 8a to 10b and in order to optimize the heat transfer and to maximize the power to weight ratio of the transformer or the inductor, it is preferable to add cooling fins 22 on the core 10. The particular solution presented in this invention consists in the direct realization of the cooling fins 22 on the external surface 23 of the device by using the soft magnetic material itself. These cooling fins 22 are integrally formed in the structure of the core 10 and consequently they are realized in a single operation during the pressing process. The thermal conductivity of the soft magnetic composite material is high and the heat transfer from the winding 12 or the windings 12 and 12' and the core 10 to the ambiance is efficient. It is also possible to maximize the use of the magnetic material of the cooling fins to let circulate the magnetic flux in them. With such an arrangement, the volume of soft magnetic material is still reduced. In this case the fins 22 must be oriented in the direction of the magnetic flux circulation. The fins 22 can be realized on the whole external surface of the core 10 or on one part of this surface only, see for example the structure of Fig's 10a and 10b. It is represented with no fins on the horizontal surfaces 23', but it is also possible to put fins on these surfaces 23'. One can note in the structures of cores 10 presented in this invention that the optimal directions of fin orientations are always in the planes of the cylindrical symmetry, a plane passing through the revolution axis 11. The use of such cooling fins 22 allows an increasing improvement

of the power to weight ratio proportional to the power of the device.

Referring now to Fig's 11a to 11d, it is pointed out that when the electrical conductivity of the soft magnetic composite material which is used is relatively high, it is necessary to realize one or several slots 24 with a small thickness to reduce the circulation of eddy currents in the core and to minimize the magnetic losses. One can note that the planes 25 of the slots 24 must be planes of the cylindrical symmetry, planes passing through the revolution axis 11.

The classical structures of three-phase transformers and inductors with three columns are realized with E cores. There are one or several windings on each column which correspond to one phase of the three phase power supply. With the three column structure, the phase windings are magnetically coupled. Three-phase transformers and inductors can be realized by using three different cores (one core per phase) with the structures described in this invention. With such an arrangement, the phase windings can be magnetically isolated if the cores are separated from each other by airgaps, or magnetically coupled if the cores are directly stacked on each other. It is also possible to place the individual cores with a spatial phase displacement of 120 deg. To obtain a symmetrical coupling of the phase windings.

Single phase inductors with distributed airgaps can also be realized by stacking several cores with the shape of the core of Fig's 2a or 2b which possess an airgap 19 and 19' of small width. Because each core 10 is possessing a small

airgap 19, the copper losses generated by proximity effect in the winding regions 16 near the airgaps 19 is reduced.

When a transformer is realized in accordance with the present invention and a soft magnetic composite material in association with one or several rectifiers 14 using diodes 14' and/or thyristors and/or transistors, see Fig. 12, the standard IEC-555-2 on the injection of current harmonics in the AC power supply is satisfied, because the harmonic content of the magnetizing current and its amplitude are relatively low.

It is within the ambit of the present invention to cover any obvious modifications of the preferred embodiment described herein, provided such modifications fall within the scope of the appended claims.